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# Nitrate Contamination of Groundwater and Soil Management

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## Abstract

The Japanese Government set the environmental quality standard for nitrate ($NO_3$) in groundwater at 10 mg N $L^{-1}$ in 1998, based on a level considered acceptable for avoiding infant methemoglobinemia. In 1998, 6.3% of groundwater in Japan contained $NO_3$ exceeding 10 mg $L^{-1}$, with agriculture regarded to be a primary source of the $NO_3$ (Environmental Agency, Japan, 1999). This paper aims to define the mechanisms of $NO_3$ contamination of groundwater associated with soil management in arable land.

The author gives an overview of the relation between nitrogen (N) fertilization and groundwater contamination. First of all, the utilization efficiency of N fertilizers for outdoor cultivation of vegetables is usually 50% or less (Nishio, 2001; Vance, 2001). Although N fertilizer is essential for crop production, excessive N could leach out of arable soils and eventually cause $NO_3$ contamination of groundwater. However, conversely, excessive N is necessary as insurance in some cases, such as when there is heavy rainfall immediately after fertilization. It should be also noted that some vegetables physiologically require a high content of N in soil even at harvest.

Nitrate leaching from different fertilizers was monitored for 7 years and the data were evaluated using an N and water balance equation (Maeda et al., 2003). Excessive N from chemical fertilizers caused substantial $NO_3$ leaching, while compost application was promising to achieve high yields and low N leaching during a few years but led to the same level of $NO_3$ leaching as that in the plots subjected to chemical fertilizer application over longer periods of time. Thus, it is of importance to predict the N mineralization rates both for manure and for soil under natural conditions. Experimental results of this kind can provide full information on N dynamics in fields for policy decisions or regulations to reduce $NO_3$ leaching while maintaining crop yields. Likewise, we must consider other influencing factors such as soil types, climatic conditions, and cropping systems for this purpose.

## Key words

Andisols, Fertilizer, Groundwater, Leaching, Manure, Methemoglobinemia, Nitrate, Nitrogen cycle

# Introduction

The provision of a safe and stable supply of food and water is essential for mankind. The increase in the world population was supported by the improvement of agricultural practices, including fertilizer application, irrigation, and plant breeding. In fact, total production of cereals in the world has increased by a factor of 2.3 while the world population has increased by a factor of 1.9 since 1961 (Fig. 1). Particularly, chemical fertilizers have played a major role in the increase of cereal production (Brown, 1999) and their world consumption has increased as much as 7.4 times since 1961 (Fig. 1). Also, the large population in the world requires more water for agriculture, industry, and living conditions (Brown, 1999). Groundwater became more important as an alternative source of water supply for surface water, because the water quality of surface waters had been adversely affected by intensive human activities.

Under these circumstances, excessive application of nitrogenous fertilizers was reported to cause groundwater contamination by $NO_3$. Utilization efficiency of N fertilizers for outdoor cultivation of vegetables is usually 50% or less (Nishio, 2001; Vance, 2001). A large proportion of the unused N may leach out of the root zone and eventually to reach groundwater. In order to improve the N utilization efficiency and to minimize the risk of N leaching, farmers or policy-makers should select the most effective measures in the fields. However, the mechanisms of $NO_3$ leaching are not well understood and thereby the effects of improved practices can not be evaluated.

This paper aims to define the mechanisms of $NO_3$ contamination of groundwater associated with soil management in arable land. First, human concern and standard limits related to the $NO_3$ concentration in water were presented. Second, the current status of groundwater contamination was described in some countries. Also, the reason why fertilizer is applied at higher N rates than the amount that crops would take up throughout the growing period was given based on the N uptake patterns of crops. Then, N dynamics in soil and factors influencing $NO_3$ leaching were reviewed. Lastly, agricultural management practices to mitigate $NO_3$ contamination of groundwater were discussed.

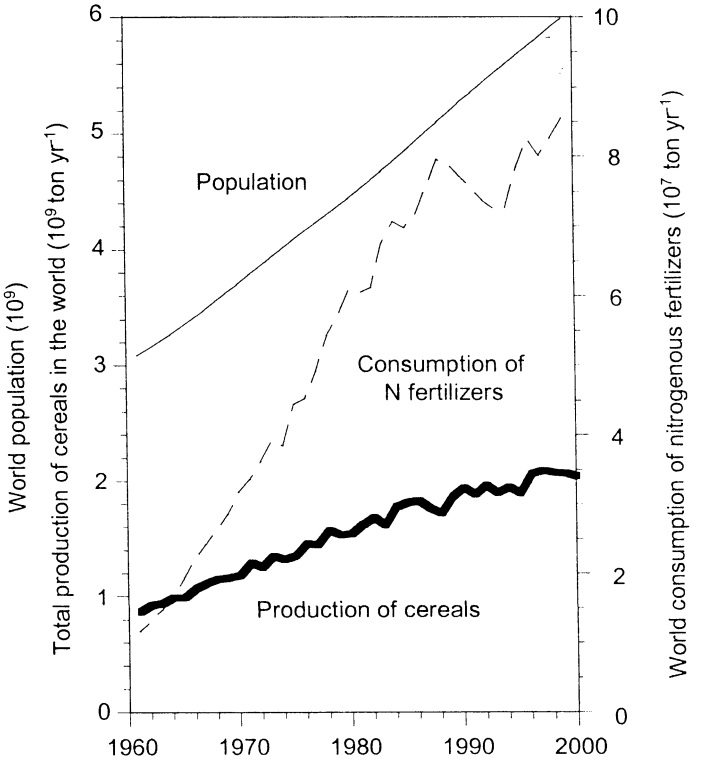



Fig. 1. Trends of population (thin line, left axis for scale), total production of cereals (thick line, left axis for scale), and consumption of nitrogenous fertilizers (broken line, right axis for scale) in the world since 1961. Illustrated from data by FAO (2001).

## Health concern related to nitrate in groundwater

Nitrate contamination of groundwater has received considerable attention due to potential human health impacts from groundwater use for drinking water. Nitrate causes a problem when it is converted to nitrite ($NO_2$), while nitrate ($NO_3$) itself is not toxic. The toxicity of $NO_2$ is associated with methemoglobinemia, which occurs when $NO_2$ oxidizes hemoglobin to methemoglobin, resulting in a decrease in the oxygen-carrying capacity of blood (Addiscott et al., 1991; Canter, 1996). Infants under 3 mo of age are the most susceptible because their stomach is not acid enough to inhibit the microbes that convert $NO_3$ to $NO_2$ (Canter, 1996).

The World Health Organization (WHO) recommended guidelines for drinking water quality ($NO_3$: $\leq$50 mg $NO_3$ $L^{-1}$; $NO_2$: $\leq$0.2 mg $NO_2$ $L^{-1}$) in 1992, and the U.S. limit for $NO_3$-N in drinking water is 10 mg N $L^{-1}$ (Canter, 1996), to offer the greatest protection to infants. The European Community (EC) directive (80/778/EEC) implements the WHO recommendation. In Japan, the water quality standard of $NO_3$-N for drinking water has been 10 mg N $L^{-1}$ since 1958 and that of $NO_2$-N (0.05 mg N $L^{-1}$) was added into the items relating to

monitoring for drinking water in 1998. In addition, the Japanese Government established an environmental quality standard for $NO_3$-N in groundwater at 10 mg N $L^{-1}$ to preserve water supply sources (Hayami, 1993) and enforced the Basic Law on Food, Agriculture, and Rural Areas to promote food self-sufficiency and sustainable agriculture in harmony with the surrounding environment in 1999.

Another aspect for environmental concern is the potential eutrophication in closed water bodies like lakes and closed seas (Koshino, 1976; Tabuchi and Takamura, 1985), where increased N levels promote the growth of algae, resulting in a decrease in the amount of dissolved oxygen. Eutrophication should be avoided due to the simplification of the ecosystems in the water bodies and the implication for drinking water supply affected by the growth of toxic algae.

## Status of groundwater contamination by nitrate and fertilizer application

Western countries have turned their attention to $NO_3$ in groundwater since the 1960s because their major source of drinking water is groundwater (Ooe et al., 1999; Ogawa, 2000), as shown in Table 1 (Kobayashi, 1994). According to the U.S. Environmental Protection Agency (EPA), 1.2% of community water system wells and 2.4% of rural domestic wells were projected to contain more than 10 mg $L^{-1}$ $NO_3$-N; approximately 4.5 million people drank nitrate-contaminated water (U.S. EPA, 1992). Also, in the European countries, drinking water sources are contaminated by $NO_3$, exceeding the WHO guidelines of 11.3 mg N $L^{-1}$ (Kumazawa, 1999). In France, more than 1 million people drank water that contained more than 11.3 mg $L^{-1}$ $NO_3$-N in 1981, with groundwater accounting for 91% (Fried, 1991). In the U.K., $NO_3$-N concentrations were found to exceed 11.3 mg $L^{-1}$ in 192 wells for drinking water in 1990, and such polluted areas were designated as nitrate-sensitive areas (Ogawa, 2000).

Table 1. Contribution of groundwater to drinking water supply in selected countries.

| | Year | Water supplied population (× 1000 persons) | Ratio of groundwater to drinking water supply (%) |
|---|---|---|---|
| Denmark | 1986 | 3,084 | 100 |
| France | 1986 | 54,500 | 64 |
| West Germany | 1986 | 59,900 | 64 |
| Netherlands | 1986 | 14,590 | 59 |
| Italy | 1984 | 51,943 | 50 |
| Finland | 1986 | 39,710 | 49 |
| U.S.A. | 1986 | 219,000 | 30 |
| U.K. | 1986 | 56,000 | 28 |
| Sweden | 1986 | 7,242 | 25 |
| Spain | 1986 | 37,200 | 24 |
| **Japan** | **1986** | **113,859** | **22** |

After Kobayashi (1994).

In eastern and central England, $NO_3$ concentrations were increasing in groundwater, which provides 30-50% of drinking water (Spalding and Exner, 1993). Eight percent of the public waterworks in Denmark and 5% of those in former West Germany supplied groundwater containing more than 11.3 mg $L^{-1}$ $NO_3$-N (Fried, 1991). In the Netherlands, the average concentration of $NO_3$-N in 56 shallow wells was 20 mg $L^{-1}$ with the highest value being 81 mg $L^{-1}$ (Ogawa, 2000). In Japan, a national groundwater survey conducted by the Environment Agency revealed that 9% in 1982 and 6.3% in 1998 of groundwater contained more than 10 mg $L^{-1}$ $NO_3$-N (Environment Agency, Japan, 1993; 1999).

Agriculture was reported to be a primary source of $NO_3$ contamination in groundwater (Kawanishi et al., 1991; Hallberg and Keeney, 1993; Kumazawa, 1999; U.S. Geological Survey, 1999). The Royal Society in the U.K. estimated that the total amount of N leached from agricultural land was about 326,000 t in 1987 while N inputs from sewage and industrial effluent to freshwater and lakes were 150,000-160,000 t (House of Lords, 1989). In the Big Spring Basin of northeastern Iowa, which is fully used for agriculture, the $NO_3$-N concentration increased from 3 mg $L^{-1}$ in the 1960s to nearly 10 mg $L^{-1}$ in the early 1980s, while the amount of fertilizer N applied in the areas increased 2.5 to 3 times as a function of increasing rates of N application as well as the increase in the vegetated area (Hallberg, 1986). In Japan, $NO_3$-N concentrations exceeding 10 mg $L^{-1}$ were detected in 15% of agricultural wells, but only in 0.05% of the wells in paddy fields (Kumazawa, 1999). Nagai (1991) reported that the $NO_3$-N concentration in groundwater continuously increased from less than 5 mg $L^{-1}$ in

the early 1970s to 20 mg $L^{-1}$ in the late 1980s under tea fields, where N fertilizer was intensively used, in Sizuoka. Hirata (1996) documented that the $NO_3$-N concentration in groundwater reached a maximum level of 90 mg $L^{-1}$ under vegetable fields receiving N fertilizer at 500 kg N $ha^{-1}$. Ogawa (2000) showed that, below upland fields, the $NO_3$-N concentration in groundwater increased along with the direction of the groundwater flow.

Nitrogen is one of the most important plant nutrients. Needless to say, N fertilizer played an important role in the Green Revolution in the 1960s. National average nitrogenous fertilizer application rates, which were calculated from the data provided by the Food and Agriculture Organization (FAO, 2001), are listed in Table 2. Necessary N doses are different among countries owing to the difference in cover corps and climate conditions. Nitrogen application rates had increased in all the countries, especially in the developed countries from 1961 to 1979 (Table 2). Since the late 1970s, the N application rates have decreased in some developed countries (indicated as III), including Japan, because of the awareness of the excess application. On the other hand, the N application rates are still increasing in developing countries (indicated as I). The national average N application rate in Japan is not high in this list and is decreasing. Nevertheless, groundwater contamination by $NO_3$ has been reported, as mentioned above.

Nitrogen application rates widely ranged from 90 kg $ha^{-1}$ for rice to 958 kg $ha^{-1}$ for celery in Japan (Table 3; Nishio, 2001).

Table 2. National average N fertilizer applications to arable land in selected countries, in 1999, 1979, and 1961 (kg N $ha^{-1}$).

| | Type[a] | Year | | |
|---|---|---|---|---|
| | | 1961 | 1979 | 1999 |
| World average | I | 9 | 43 | 63 |
| Ireland | I | 18 | 218 | 399 |
| Netherlands | III | 245 | 619 | 375 |
| Egypt | I | 77 | 217 | 354 |
| South Korea | I | 107 | 215 | 265 |
| Malaysia | I | 32 | 138 | 255 |
| U.K. | II | 69 | 192 | 220 |
| China | I | 5 | 109 | 196 |
| Viet Nam | I | 3 | 16 | 195 |
| Sri Lanka | I | 61 | 90 | 186 |
| Germany | III | 72 | 185 | 170 |
| France | II | 32 | 123 | 140 |
| Bangladesh | I | 2 | 29 | 124 |
| Norway | III | 58 | 136 | 121 |
| Chile | I | 4 | 15 | 119 |
| Denmark | III | 48 | 149 | 110 |
| Indonesia | I | 5 | 34 | 109 |
| **Japan** | **III** | **112** | **159** | **106** |
| Greece | III | 30 | 122 | 105 |
| Italy | III | 27 | 117 | 101 |
| New Zealand | I | 2 | 9 | 100 |
| Philippines | I | 7 | 44 | 87 |
| Spain | I | 20 | 58 | 86 |
| Finland | II | 22 | 82 | 81 |
| India | I | 2 | 21 | 79 |
| Thailand | I | 1 | 9 | 73 |
| Sweden | III | 31 | 86 | 69 |
| U.S.A. | II | 17 | 55 | 64 |
| Mexico | I | 6 | 36 | 52 |
| Canada | I | 2 | 18 | 35 |
| Brazil | I | 3 | 21 | 31 |
| Australia | I | 1 | 6 | 23 |
| Kenya | I | 1 | 5 | 15 |

[a] I, Increased throughout the period 1961-1999; II, Increased from 1961 to 1979, then did not change;
III, Increased from 1961 to 1979, then decreased to 1999.

Excessive N in soil, which is shown as surplus N in Table 3, may cause large N gaseous and leaching losses from arable land, unless the patterns of N uptake by crops match N available in soil. Conversely, some excessive N is necessary as insurance when considering the N losses. Rainfall immediately after fertilization would bring a considerable amount of mineral-N in soil to deeper vadose zones, because crops at an early stage had not absorbed much N in soil by that time.

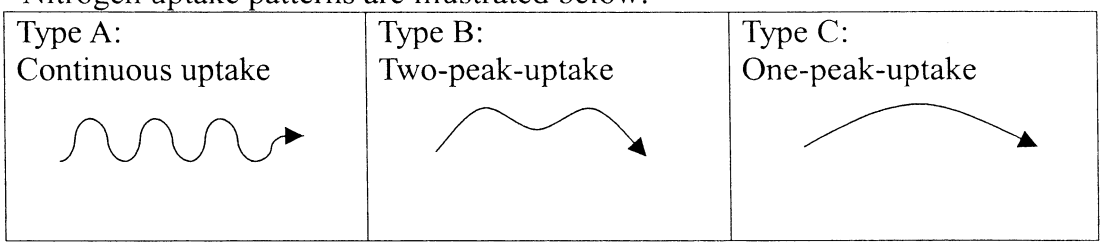
Nitrogen surplus increased with the N application rate (Table 3). Generally, crops need more N in soil at the stage of vegetative growth than at that of reproductive growth. Leaf vegetables such as celery and spinach are harvested at the stage of vegetative growth. Fruit vegetables such as tomato are continuously harvested at the stages of both vegetative and reproductive growth. Accordingly, leaf and fruit vegetables require a large amount of N in soil throughout the growing period, even at harvest (Type A), which induces more $NO_3$ leaching during the bare period after harvest. On the other hand, the crops of Types B and C do not need much N in soil at harvest because head-formating vegetables such as cabbage in Type B are harvested at the late stage of vegetative growth and other crops in Type C at the stage of reproductive growth (Souma, 1988). This is the reason for the larger N application rates for crops in Type A.

Adequate application of livestock manure to arable land is recommended for recycling valuable nutrient resources. In addition, some consumers have tended to prefer agricultural products grown with organic fertilizers in the last decade. The average application rate of manure (60 kg N $ha^{-1}$) is half as much as that of chemical fertilizer (113 kg N $ha^{-1}$) in Japan (Mishima et al., 1999). Although mineralized N from organic-N in manure must be considered as N input to arable land, evaluation of the mineralization rate of organic-N in manure is not easy (Addiscott, 1991).

Table 3. Nitrogen balance in fields for selected crops in Japan (modified after Nishio, 2001; Souma, 1988).

| N uptake pattern[a] | Crop | Mineral N application (kg N $ha^{-1}$) | N uptake (kg N $ha^{-1}$) | N surplus (kg N $ha^{-1}$) |
|---|---|---|---|---|
| Type A | Celery | 958 | 226 | 732 |
| | Egg plant | 643 | 160 | 483 |
| | Tea | 628 | 278 | 350 |
| | Tomato | 321 | 101 | 220 |
| | Spinach | 220 | 63 | 157 |
| Type B | Chinese cabbage | 315 | 130 | 185 |
| | Cabbage | 338 | 217 | 121 |
| Type C | Onion | 248 | 93 | 155 |
| | Water melon | 161 | 72 | 89 |
| | Potato | 156 | 74 | 82 |
| | Radish | 133 | 94 | 39 |
| | Rice | 90 | 96 | -6 |

[a] Nitrogen uptake patterns are illustrated below:




## The nitrogen cycle in arable land

The N cycle is shown in Fig. 2. The main N inputs to arable land are the application of fertilizer and manure, and precipitation. The most common N fertilizer is urea (49% of total domestic demand in 1996; MAFF, 1998), followed by ammonium sulfate (20%), high-analysis compound fertilizer (13%), and ammonium phosphate (11%). Air-borne N inputs amount to about 10 kg N $ha^{-1}yr^{-1}$ (Tabuchi and Takamura, 1985; Hirata, 1996).

Nitrogen can exist in various forms in soil. In most of the soils, more than 90% of soil-N occurs in organic forms (Vinten and Smith, 1993). The decomposition of organic matter converts some organic-N to mineral-N ($NH_4$-N, $NO_2$-N, $NO_3$-N) through microbial processes (mineralization). At the same time, mineral-N can be converted to organic-N by microbial assimilation

(immobilization). Ammonium N is oxidized to $NO_2$-N and then $NO_3$-N by microorganisms (nitrification). Crops take up mineral-N from fertilizer or N mineralized from organic matter. Gaseous N losses occur due to denitrification under anaerobic conditions and ammonium volatilization under alkaline conditions. Furthermore, a considerable extent of $N_2$ fixation occurs in specialized groups of microorganisms for grain and pasture legumes.

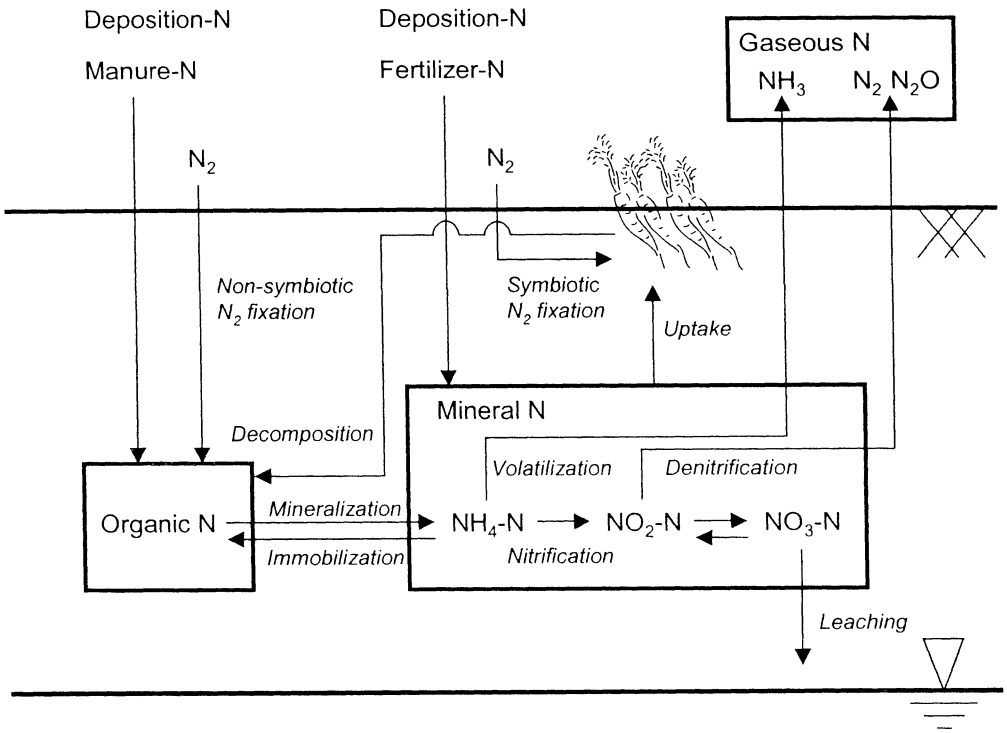



Fig. 2. Nitrogen cycle in soil.

## Nitrate leaching and influencing factors

Nitrate leaching is the process whereby $NO_3$ in the soil solution is displaced from root zones by rainfall or irrigation water and eventually penetrates into groundwater (Fig. 2). General knowledge of the N cycling must be considered to select fertilization practices in a field. Nitrate N is freely leached below root zones, while $NH_4$-N is adsorbed onto the soil surface with negative charges. A number of agricultural practices and hydrogeological factors influence $NO_3$ leaching. The magnitude of the adverse impacts of these factors must be evaluated to improve agricultural management, resulting in the maintenance of crop yield while reducing $NO_3$ leaching.

We studied $NO_3$ leaching in a Japanese Andisol treated with three types of N fertilizers in addition to a control (SC: swine compost, CU: coated urea, AN:

ammonium N, or NF: no fertilizer) for 7 years (Maeda et al., 2003). Sweet corn (*Zea mays* L.) was grown in summer, followed by Chinese cabbage (*Brassica rapa* L. var. *amplexicaulis*) or cabbage (*Brassica oleracea* L. var. *capitata*) in autumn each year. In the chemical fertilizer plots treated with AN or CU, the $NO_3$-N concentration in soil water at 1-m depth increased markedly in the summer of the second year and fluctuated between 40–60 mg $L^{-1}$ and 30–50 mg $L^{-1}$, respectively (Fig. 3). The difference in $NO_3$-N concentrations in soil water between the CU and AN plots probably resulted from differences in crop uptake of N from respective

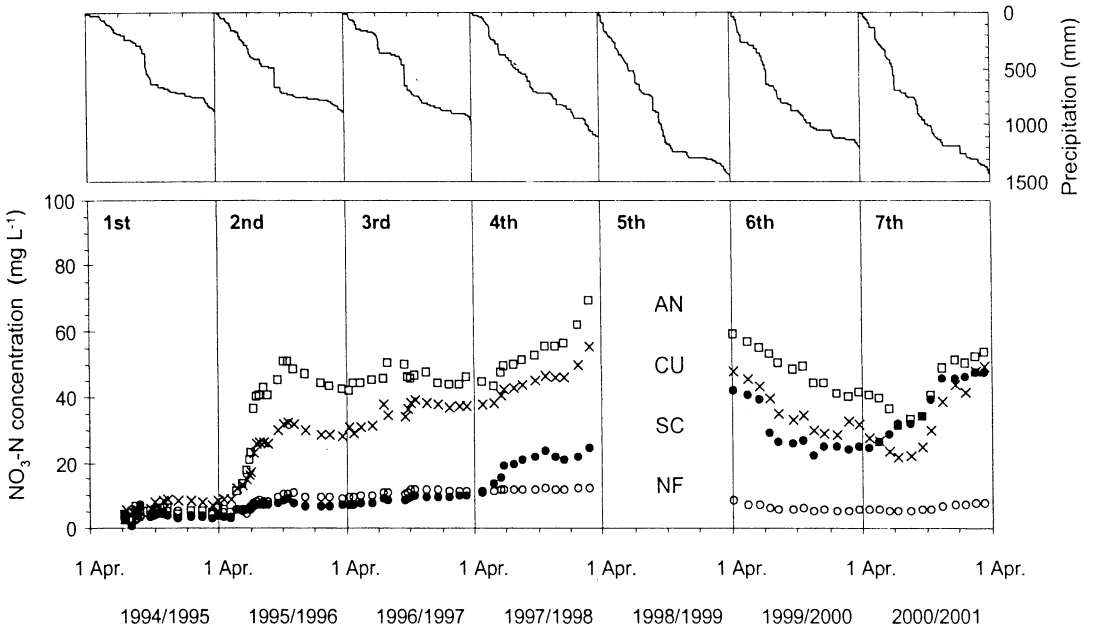



Fig. 3. Nitrate concentration of soil water at 1-m depth treated with different fertilizers. SC: swine compost, CU: coated urea fertilizer, AN: ammonium fertilizer, NF: no fertilizer. From Maeda et al. (2003).

sources. Matsumaru (1997b) also demonstrated that, based on a lysimeter study, slow-release fertilizer could markedly increase the yield of and N uptake by upland rice and taro in sandy soil, resulting in the suppression of N leaching, compared with conventional chemical fertilizer. In the SC plot, the $NO_3$-N concentration started increasing in the fourth year, reaching the same level as in the AN and CU plots in the late period of the experiment (Fig. 3). Increasing N mineralization owing to the lowered C/N ratio of the soil resulted in an increase in $NO_3$-N concentration at 1-m depth in the late period of the experiment. It is also likely to occur that the residual organic N from previously applied manure was mineralized, so that the total amount of mineralized N increased over the years (Angle et al., 1993; Thomsen et al., 1993; Bergstöm and Kirchmann, 1999). Repeated application of composts may simultaneously increase the risk

of serious $NO_3$ leaching, although the level of soil fertility may increase (Addiscott et al., 1991).

The following N and water balance equation on the soil surface (OECD, 1999) was used for predicting $NO_3$-N concentration in soil water at 1-m depth (Maeda et al., 2003):

$$PNC = \frac{PNP}{EW} \times 100 \quad [1]$$

where *PNC* (mg $L^{-1}$) is the potential nitrate concentration, *PNP* (kg $ha^{-1}$ $yr^{-1}$) the potential nitrate present in soil, and *EW* (mm $yr^{-1}$) excess water (the difference between water input and evapotranspiration). *PNP* is obtained by subtracting the amount of N uptake, which refers to N in all parts of the crops removed from the plots, from that of N application in a year. The potential $NO_3$-N concentrations by Eq. [1] satisfactorily predicted $NO_3$-N concentrations in the AN and CU plots, but substantially overestimated that in the SC plot, presumably because a large portion of N from SC first accumulated in soil in the organic form (Table 4). Our results indicate that, under the Asian monsoon, excessive N from chemical fertilizers applied

Table 4. Potential $NO_3$-N present in soil (PNP), potential $NO_3$-N concentration (PNC) by the N and water balance equation, and 6-yr average $NO_3$-N concentration in soil water at 1-m depth.

| Fertilizer treatment | *PNP*[a] (kg $ha^{-1}$ $yr^{-1}$) | *PNC*[b] (mg $L^{-1}$) | 6-yr average $NO_3$-N[c] (mg $L^{-1}$) |
|---|---|---|---|
| SC | 571 | 99 | 16 |
| CU | 192 | 33 | 28 |
| AN | 214 | 37 | 36 |
| NF | −43 | — | 7 |

From Maeda et al. (2003).

[a] *PNP* was obtained by subtracting the amount of N uptake, which refers to N of all parts of the crops removed from the fields, from that of N application in a year. Data sets during the period 1994/1995-2000/2001 were used for the calculations.

[b] *PNC* was used as an estimate of $NO_3$-N concentration in soil water at 1-m depth. *EW* was estimated to be 576 mm $yr^{-1}$.

[c] Data sets during the period 1994/1995-2000/2001 except for 1998/1999 were used for the calculations.

to Andisols can cause substantial $NO_3$ leaching, while compost application is promising as a mean of establishing high yields and low N leaching during a few years, but would cause the same level of $NO_3$ leaching as in chemically fertilized plots over longer periods (Maeda et al., 2003).

Local conditions such as climate and soil type also affect $NO_3$ leaching. Nitrate concentrations of leachate increased with larger precipitation in Wisconsin (Andraski et al., 2000) and Denmark (Eriksen et al., 1999), whereas

they decreased in Minnesota (Randall et al., 1997). While watering treatment did not affect significantly $NO_3$-N leaching, soil types differing in texture and organic matter content affected it substantially (Bergström and Johansson, 1991).

Matsumaru (1997a) showed, using repacked lysimeters, that 25-32% of fertilizer-N leached out in volcanic ash soil, while 58-66% of that in sandy soil at the same application rates of fertilizer as in the volcanic ash soil. Andisols, volcanic ash soil, that covers more than half of the upland fields in Japan have high anion exchange capacity (AEC). High AEC values of soil are often significant for $NO_3$ adsorption (Katou et al., 2001). Preferential water flow in soil brings $NO_3$ to groundwater quickly (Maeda and Bergström, 2000). Preferential flow refers to macropore flow, fingering, and funneled flow (Steenhuis et al. 1995). Macropores, which reflect soil structure, root decay, wormholes, etc., constitute preferred flow pathways for infiltration of water in soil. Fingering occurs due to wetting front instability such as changes in hydraulic conductivity with depth and compression of air ahead of the wetting front. Funneled flow takes place when sloping geological layers cause pore water to flow laterally, accumulating in a low region. Many soil scientists have conducted studies on the complicated water flows in soil, but still their results are not easily adaptable to the prediction of $NO_3$ leaching.

## Measures for the prevention of nitrate contamination

The attention of the present paper focused on measures for the prevention of $NO_3$ contamination from the viewpoint of the 'polluter pays' principle. In addition, the remediation of contaminated groundwater is difficult and costly, since contaminants from a non-point source like arable land tend to diffuse. Preventive measures for minimizing agriculturally based $NO_3$ contamination of groundwater are listed in Table 5. Measures for the treatment of $NO_3$ in groundwater were reviewed by Canter (1996).

Several technical measures can be used for reducing $NO_3$ leaching in arable land. The basic concept is associated with matching available N in root zones to meet crop N demand all the time. Slow-release fertilizers, mulches, effective application methods of fertilizer, and use of catch crops can improve N recovery rates by crops, resulting in high yields and low N leaching. Fertilization management influences the amount of available-N in
soil for crops. Substitution of slow-release fertilizers for readily available conventional fertilizers suppressed N leaching in short-term studies (Sakata et al., 1995; Matsumaru, 1997b). Mulching with a plastic film can lead to the increase of crop yields and reduction of N leaching by improving the water and biological conditions in soil (Islam et al., 1994). Split applications or banding of fertilizer reduced $NO_3$ leaching (Power et al., 2000). Nitrate leaching is also affected by manure types with different amounts of available-N (Beckwith et al., 1998). Coordination of crop need and fertilizer application

must be taken into account depending on the climate and soil conditions.

Table 5. Management measures for mitigation of $NO_3$ impacts on groundwater.

| |
|---|
| **Technical measures:**<br>o Improvement of N recovery rates by new types of fertilizer / cropping systems / optimum coordination of crop need and fertilizer application;<br>o Recycling of organic wastes;<br>o Provision of land use barriers to N losses from agricultural watersheds. |
| **Policy measures:**<br>o The Basic Law on Food, Agriculture and Rural Areas (enacted in 1999): proper use of fertilizers; improvement of soil fertility by effective use of livestock manure;<br>o Designation of Nitrate-sensitive Areas. |
| **Educational measures:**<br>o Farmer extension service;<br>o Consumer awareness of the linkage between low-input products and the environment;<br>o Community-supported agriculture. |
| **Economic measures:**<br>o Taxation of N discharge / fertilizer;<br>o Subsidies for sustainable agriculture;<br>o Display for products grown under sustainable agriculture systems, enabling consumer choice. |

Cropping systems, tillage, and other production practices can be considered as other influencing factors. Nitrate leaching was reduced by the introduction of catch crops such as perennial ryegrass and soybean (Aronsson and Torstensson, 1998; Power et al., 2000). The effects of tillage practices on $NO_3$ leaching were often site-specific (Power et al., 2000). Nitrate leaching was larger where crop irrigation was used (Burart and Kolpin,1992).

Inadequate treatments of organic wastes from livestock industries have resulted in N enrichment of water (Tabuchi, 2001). The organic resources should be used for nutrients in fields. However, excessive use of livestock manure as well as chemical fertilizer on arable land may cause groundwater contamination (Thomsen et al., 1993; Adams et al., 1994; Chang and Entz, 1996).

Wetlands and paddy fields can be barriers to N losses from agricultural land (Tabuchi, 2001). Nitrate concentrations in stream water that had penetrated from groundwater flowing below upland fields were reduced when the water flew through paddy fields (Abe et al., 1999), because the paddy fields have a large potential of N removal by uptake and denitrification (Maeda and Ozaki, 1994).

The other measures presented in Table 5 are potentially useful in controlling $NO_3$ contamination of groundwater associated with agricultural practices. These approaches can be used either singly or in various compatible combinations.

## Conclusions

We must adopt proper measures to address water contamination by $NO_3$ immediately, because the amelioration of contaminated water resources would be impossible or is very costly. The author pointed out that balancing both effects of nitrogenous fertilizer, namely crop growth promotion and human health concern, should be considered at any levels and suggested that the mechanisms of $NO_3$ leaching must be understood to propose optimum balanced practices in a field.

Since many natural and practical factors affect $NO_3$ leaching and N dynamics are transient, we presently do not have any practical models to evaluate the long-range effect of improved soil management on $NO_3$ leaching precisely. We need develop mathematical models to propose the best soil management practices. In view of promoting sustainable agriculture, we should accumulate more knowledge on the fate of manure-N applied to fields. Moreover, preferential flow of water or solutes is another primary theme to improve the accuracy of N dynamics models.

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